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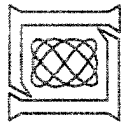
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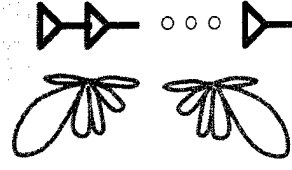
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Robust MIMO Wireless Communication in the Presence of Interference Using Ad Hoc Antenna Arrays

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& Amanda M. Chan

MIT Lincoln Laboratory

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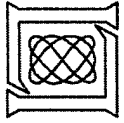


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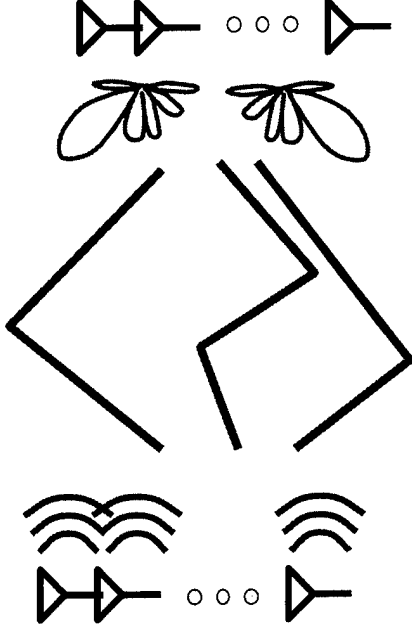
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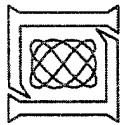


Topics

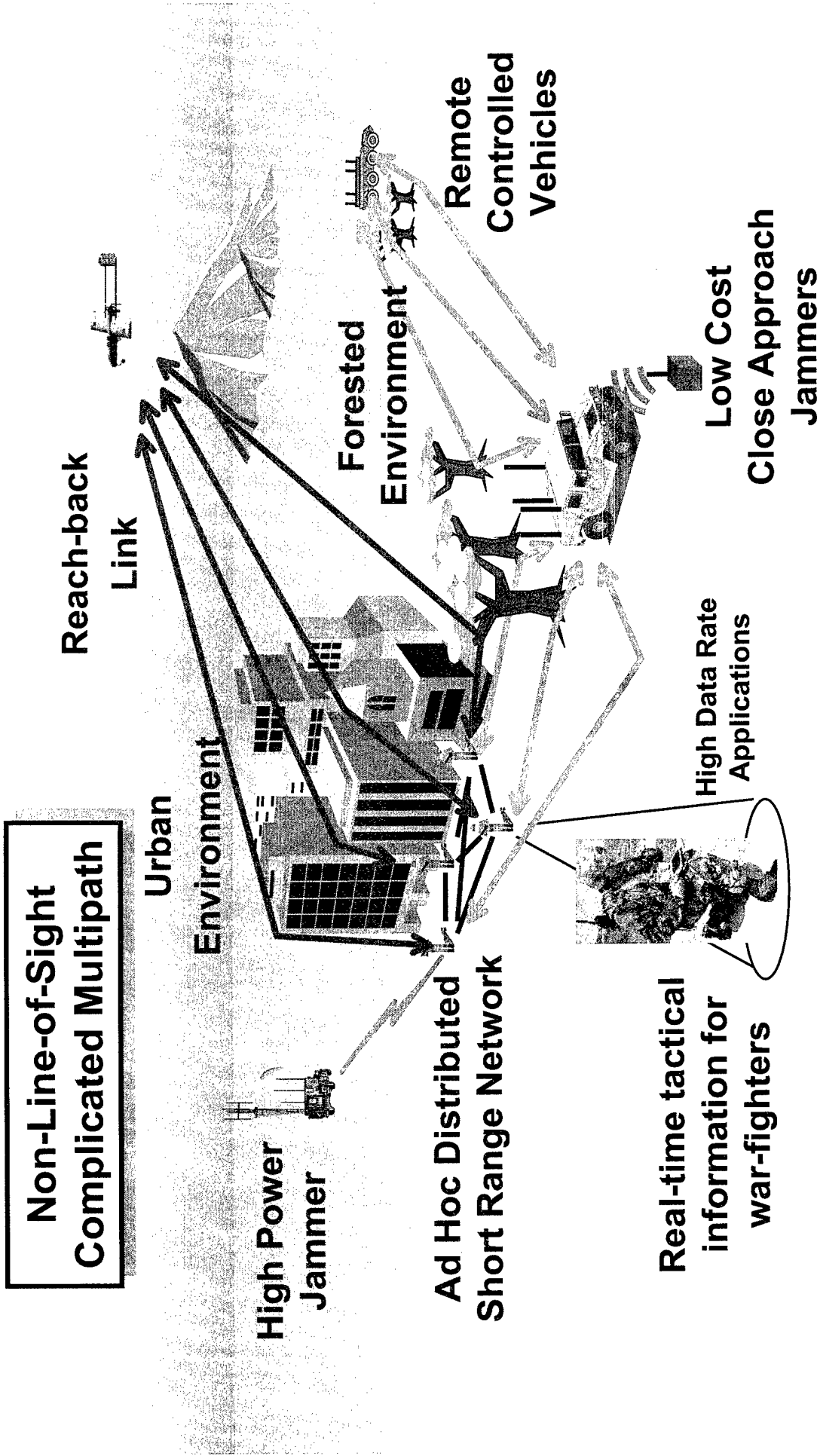
MIMO Communication

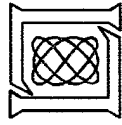
- **Introduction**
 - **Military wireless communication**
 - **MIMO definition**
 - **Ad hoc antenna networks**
- **MIMO Theory**
- **Phenomenology**
- **Receiver**





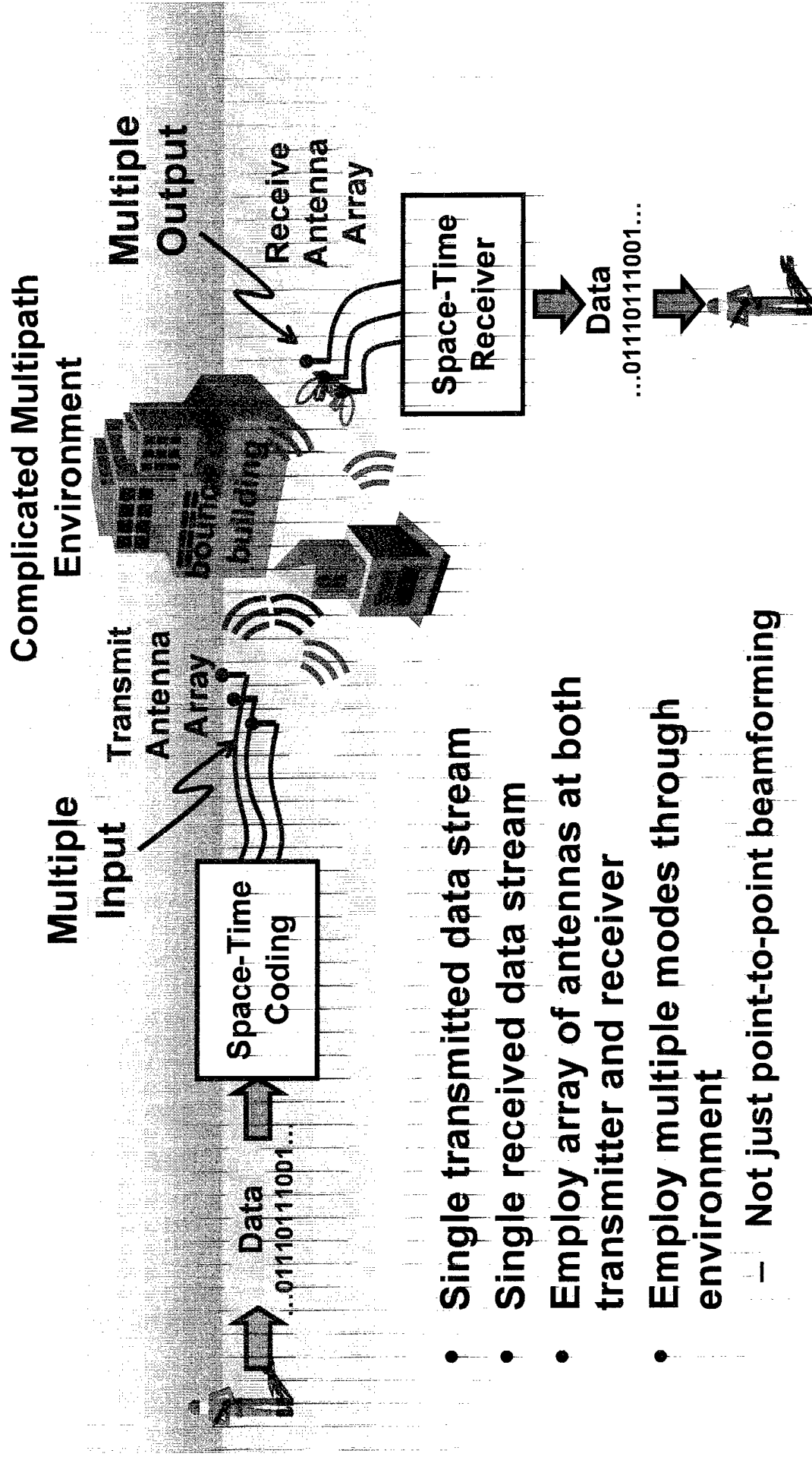
Advanced Military Wireless Communications



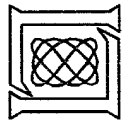


MIMO Communication

Multiple-Input Multiple-Output

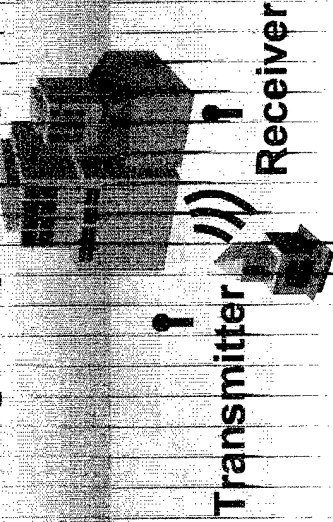


- Single transmitted data stream
- Single received data stream
- Employ array of antennas at both transmitter and receiver
- Employ multiple modes through environment
 - Not just point-to-point beamforming



Advantages of MIMO Communication

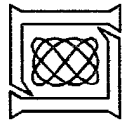
SISO Communication *Single-Input Single-Output*



MIMO Communication *Multiple-Input Multiple-Output*

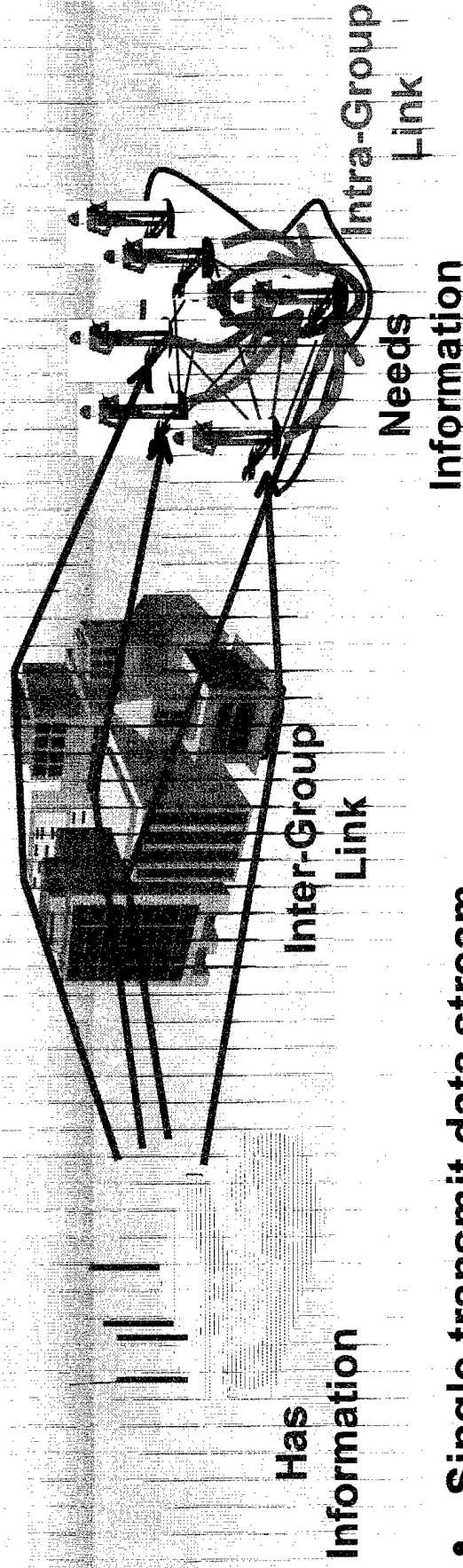


- Coherent receive beamforming
 - Gain
 - Jammer mitigation
- Transmit spatial diversity
 - Fading mitigation
 - Shadowing mitigation
 - Jammer avoidance
- Enables high spectral efficiency
 - Enables high data rates given limited bandwidths
 - Low duty cycle communication



Distributed Ad Hoc Antenna Arrays

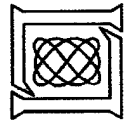
Multiple-Input Multiple-Output



- Single transmit data stream
- Single received data stream
- Employ users as antenna array
 - Coherently process received signal
- Use local network to move distributed data to/from interested user

Issues

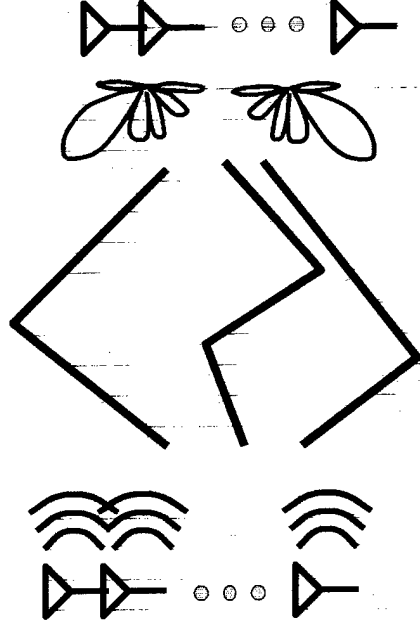
- Local networking
- Relative local oscillator errors

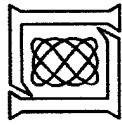


Topics

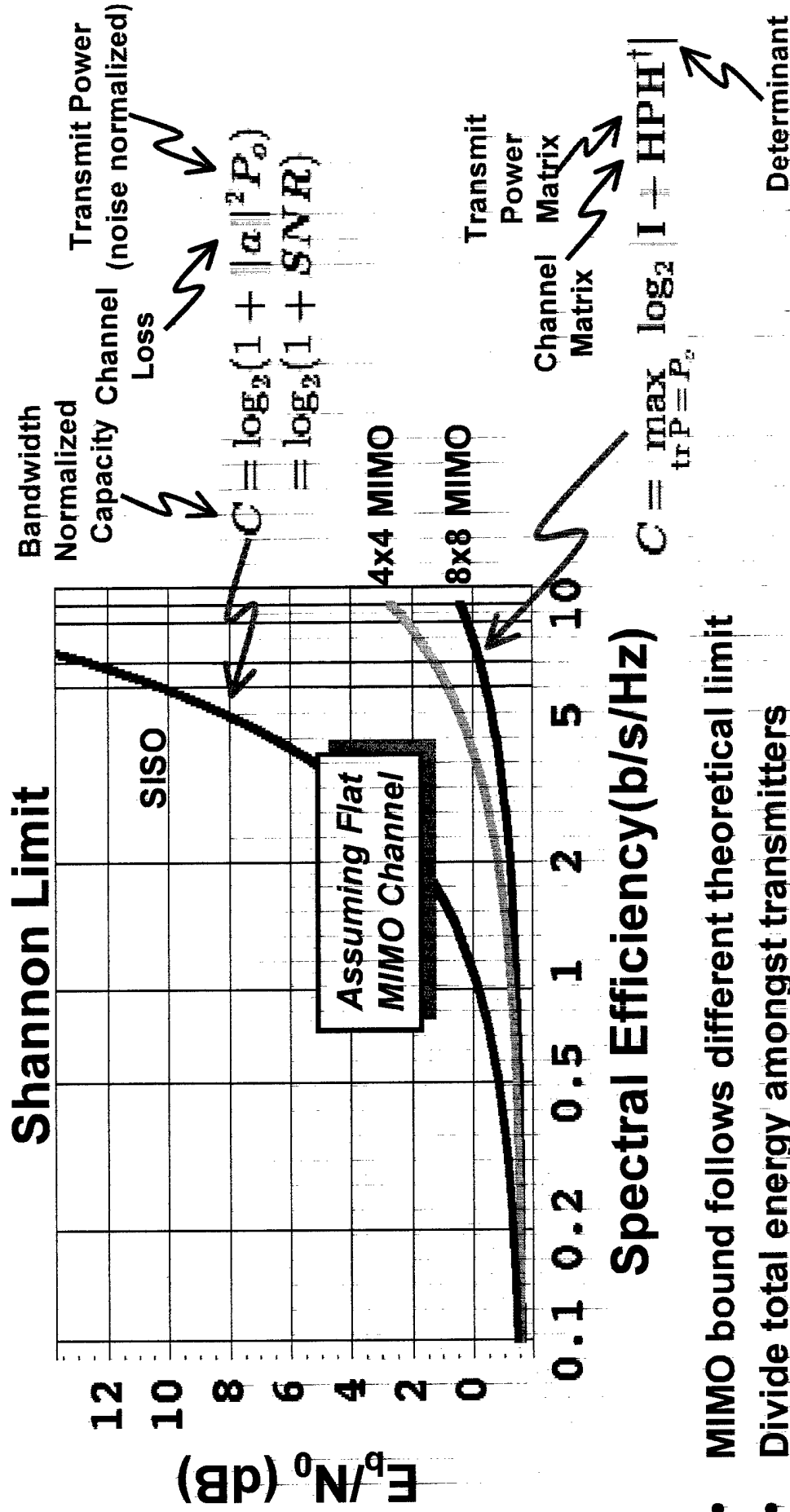
MIMO Communication

- Introduction
- MIMO Theory
 - Capacity
 - Phenomenology
 - Interference Mitigation
 - Space-Time Coding
- Phenomenology
- Receiver

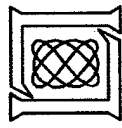




MIMO Capacity Bound



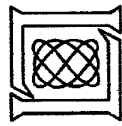
- MIMO bound follows different theoretical limit
- Divide total energy amongst transmitters avoiding compressive regime of SISO Shannon limit



MIMO Channel Knowledge

Channel knowledge affects MIMO capacity and coding

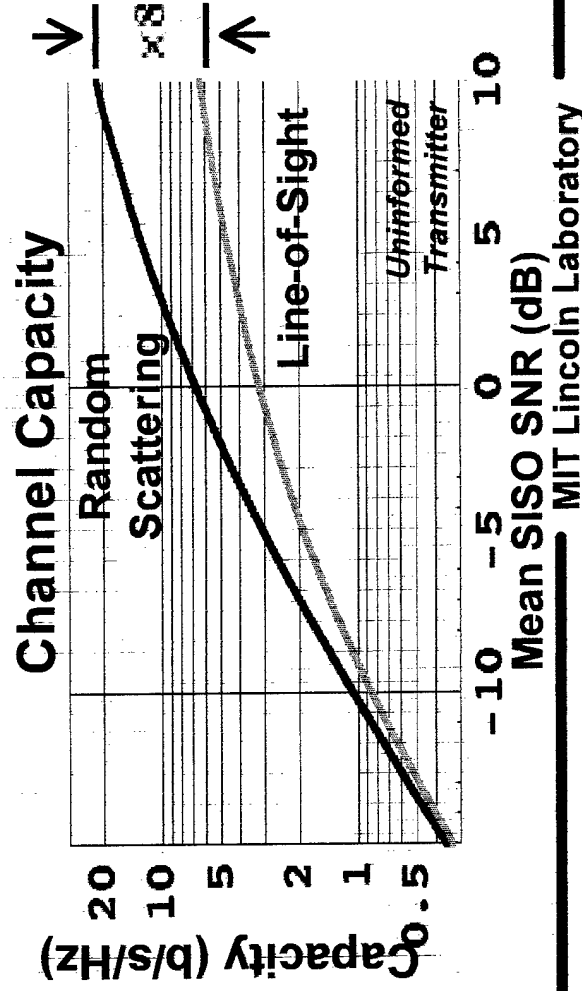
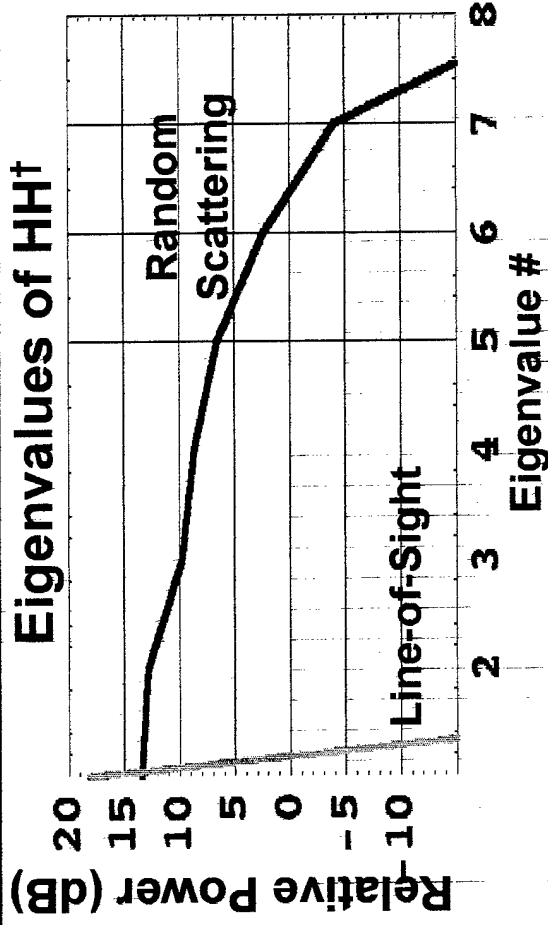
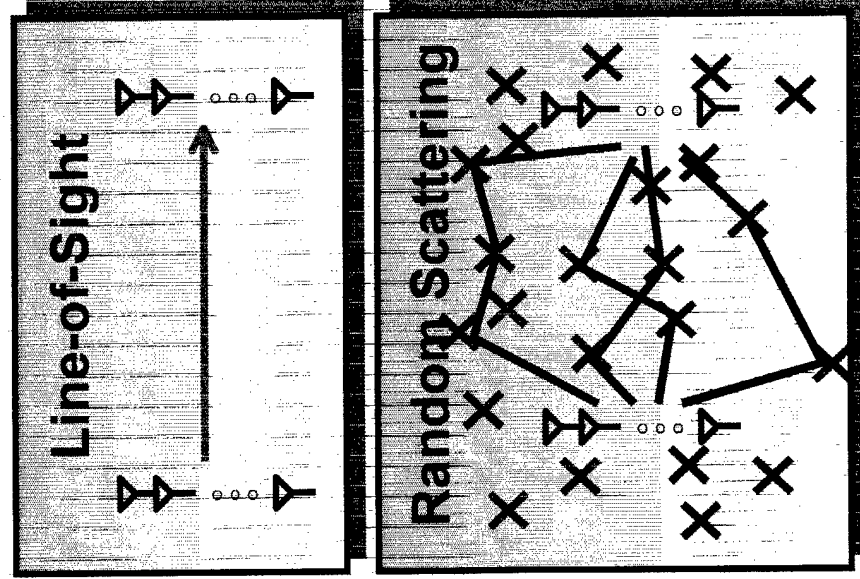
Transmitter Channel Knowledge	Informed Transmitter	Uninformed Transmitter
Channel Capacity (b/s/Hz)		
	$C_{IT} = \max_{tr\{P\}=P_o} \log_2 \mathbf{I} + \mathbf{H}\mathbf{P}\mathbf{H}^{\dagger} $ <p>Determinant Transmit Power Matrix (noise-normalized)</p>	<p>Total Power (noise-normalized)</p> $C_{UT} = \log_2 \left \mathbf{I} + \frac{P_o}{n_{Tx}} \mathbf{H}\mathbf{H}^{\dagger} \right $ <p>Number Of Transmitters Channel Matrix</p>

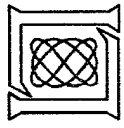


Channel Matrix

8 x 8 MIMO Example

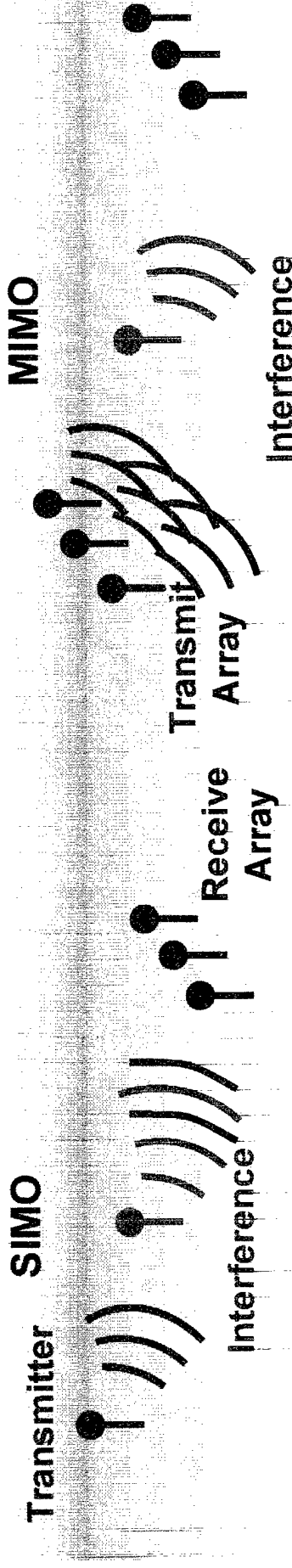
Channel matrix, H , contains complex attenuation between each transmit and receive antenna



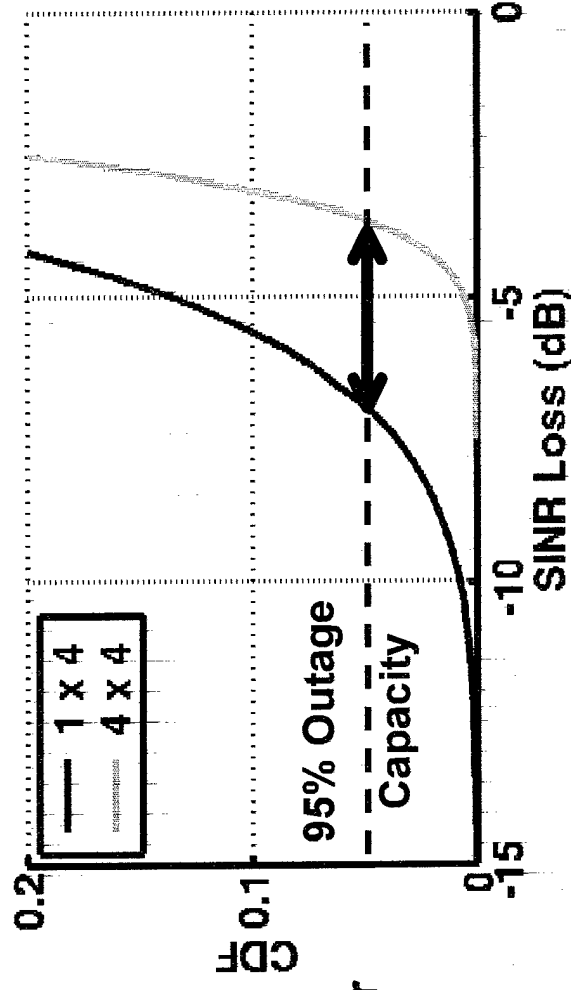


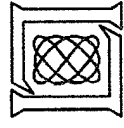
Jammer Mitigation & Avoidance

SINR Loss



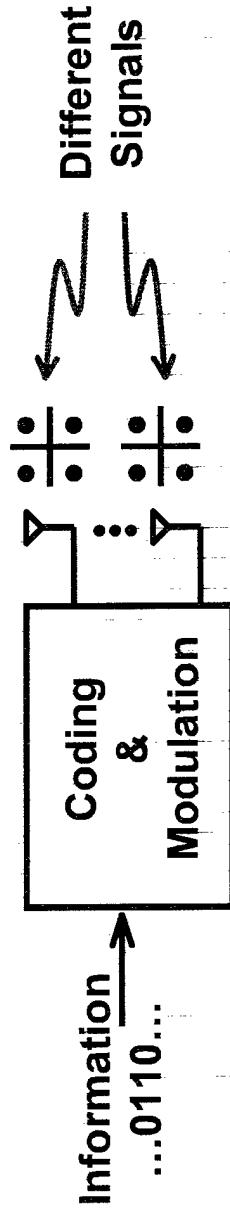
- Adaptive performance in the presence of Jammer
- MIMO has better outage capacity performance
- Assumptions
 - Single high power jammer
 - I.I.D. random Gaussian channel
 - MIMO uninformed transmitter





Space-Time Coding

- Space-time coding converts information bits to waveform distributed amongst antennas

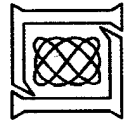


- Space-time coding analogous to conventional (SISO) coding approaches

- Trellis
- Low density parity check
- **Turbo**

Space-Time Turbo Code Example

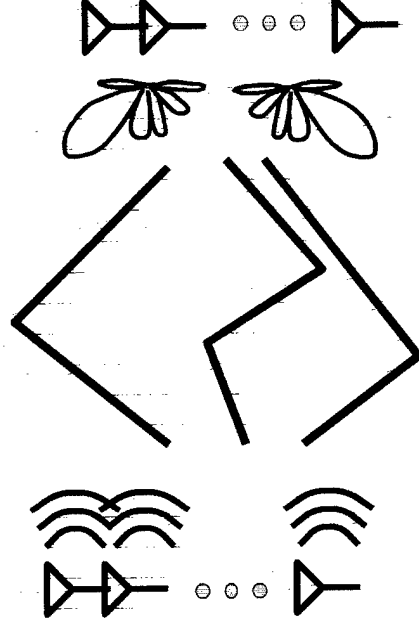
- Total data rate 2 b/s/Hz
- 4 transmit antennas
- 4096 bit interleavers
- QPSK constellations
- Uninformed transmitter

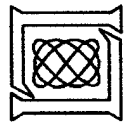


Topics

MIMO Communication

- Introduction
- MIMO Theory
- Phenomenology
 - Experimental setup
 - Phenomenology
- Receiver



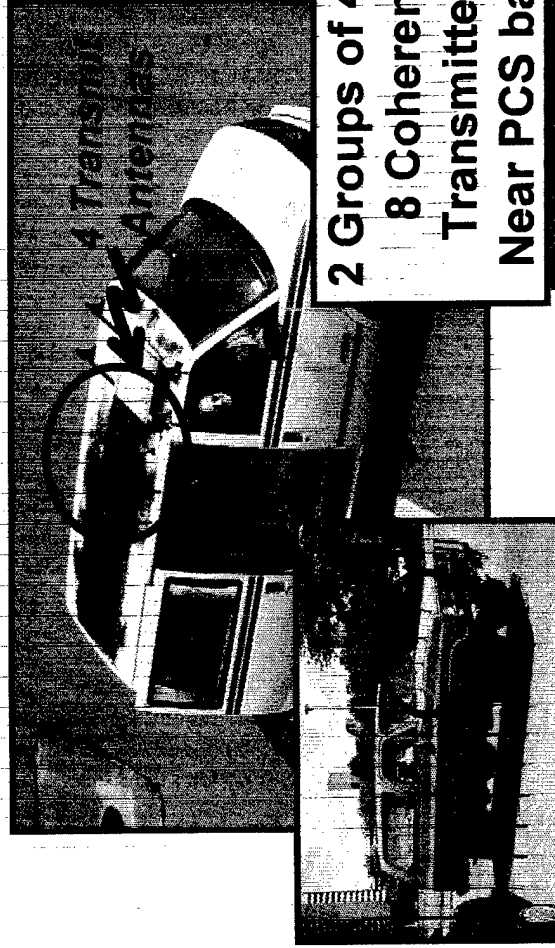
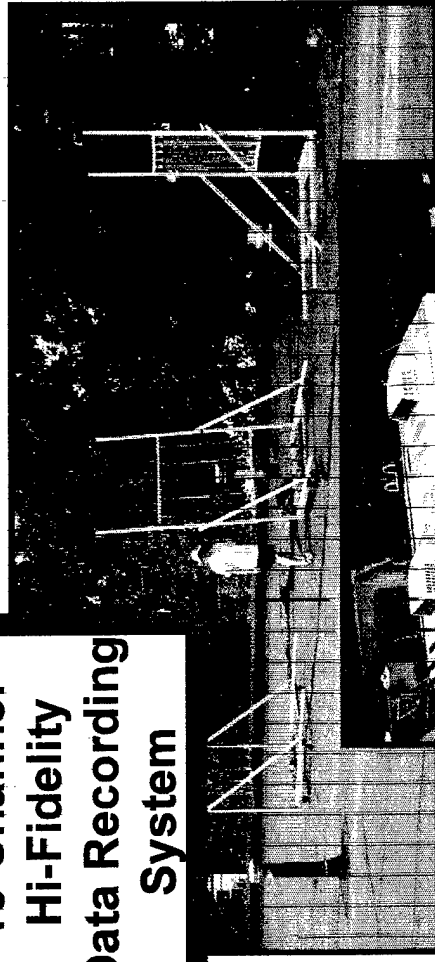


MIMO Experiment

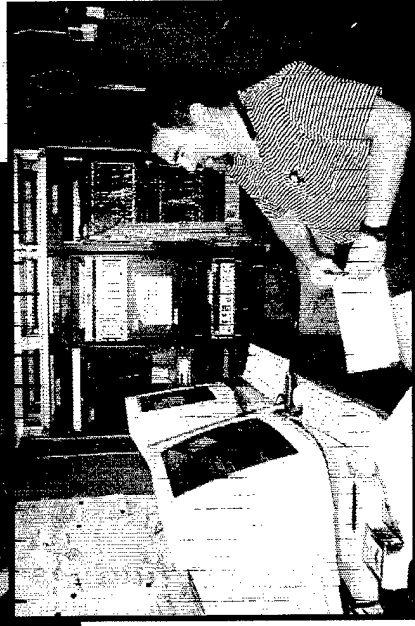
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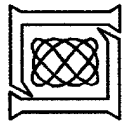
- Investigate channel phenomenology
- Study space-time coding
- Explore transmitter coherence requirements
- Demonstrate robustness to
 - Jamming
 - Cochannel interference

16-Channel
Hi-Fidelity
Data Recording
System



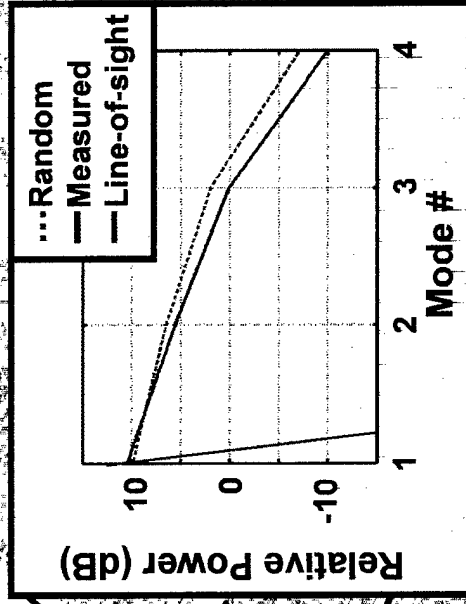
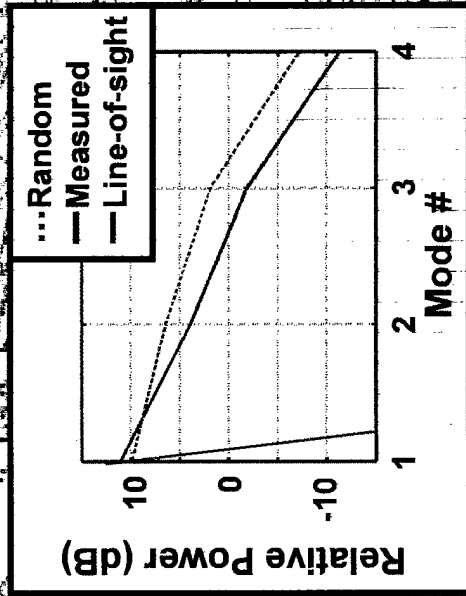
2 Groups of 4, or
8 Coherent
Transmitters
Near PCS band





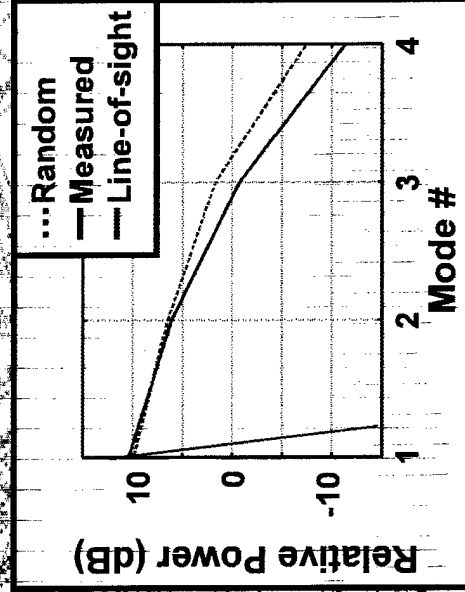
Channel Modes

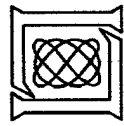
Experimental Results



Transmit
Array

Receive
Array

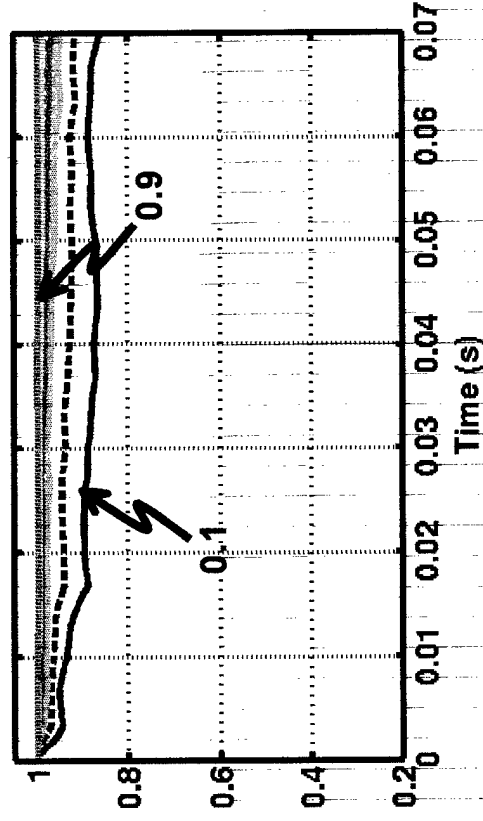




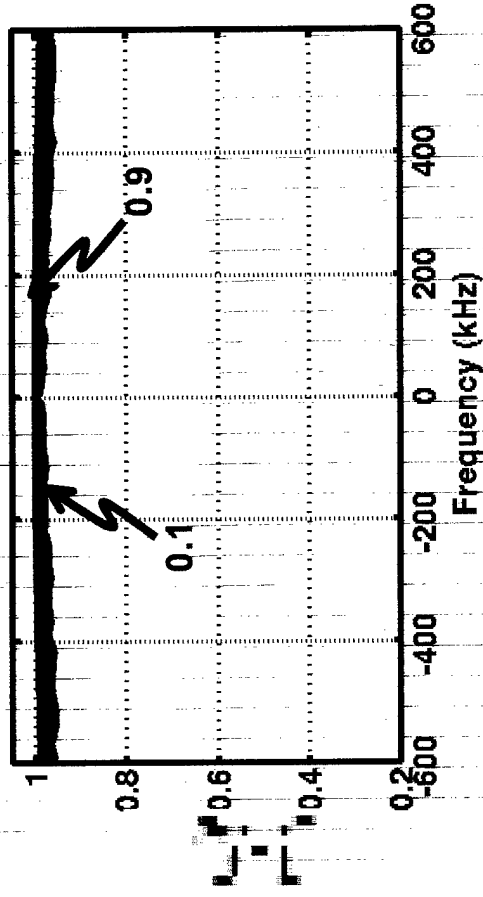
Channel Stationarity

CDF's of Power Weighted Mean $\cos^2\theta_n$

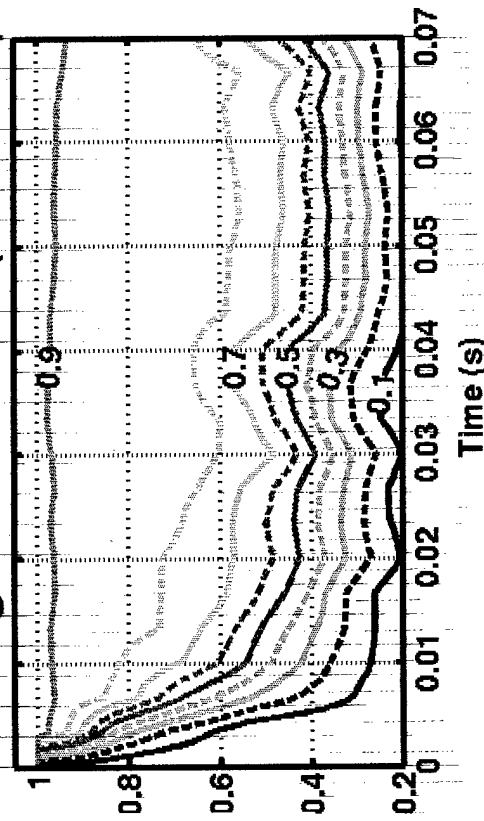
Stationary Transmitter



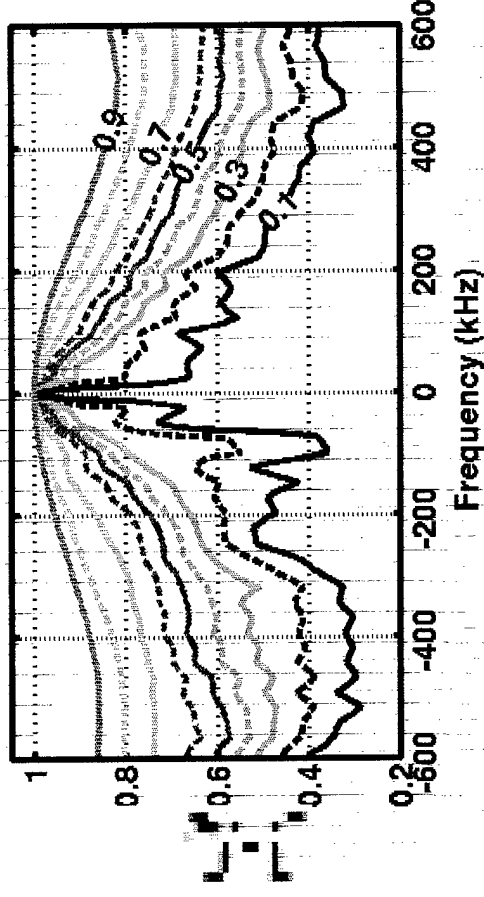
Indoor

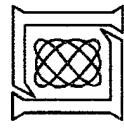


Moving Transmitter (5-10 m/s)

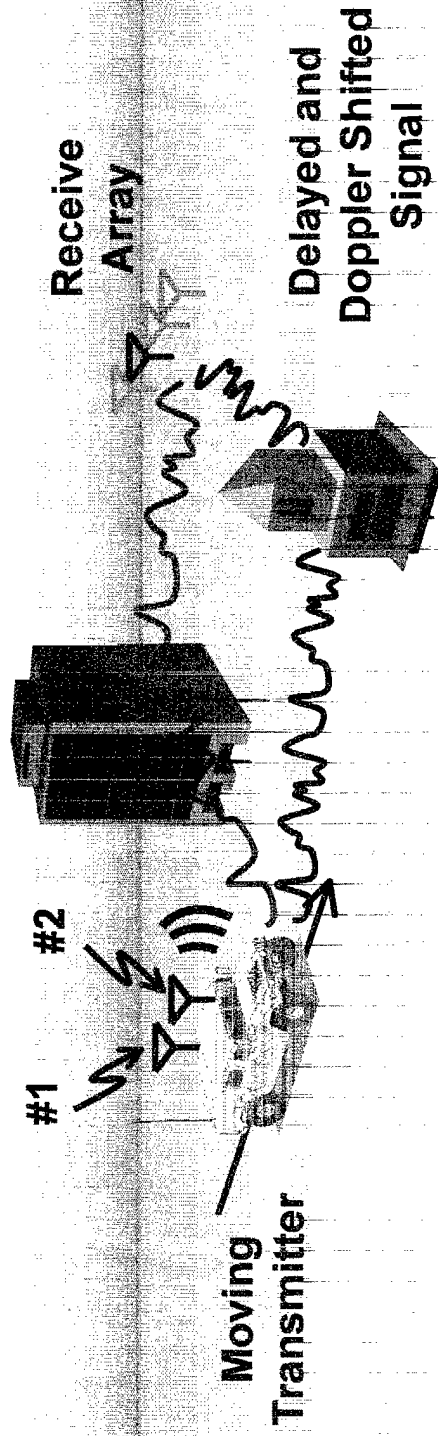


Outdoor



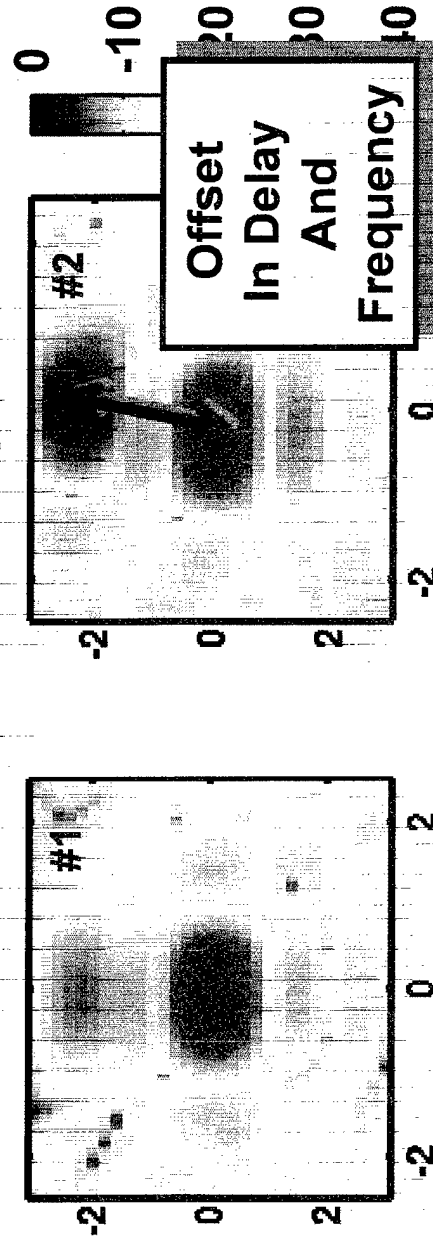


Delay-Frequency Correlations Experimental Data

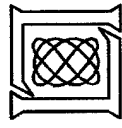


Frequency Offset
(resolution cells, 60Hz)

Time-Frequency Pulse Response



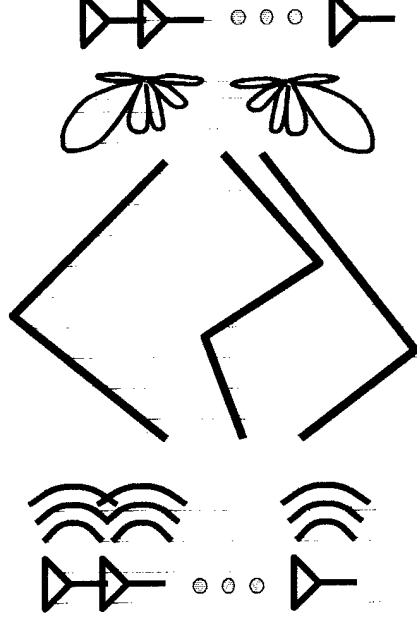
Delay (resolution cells, 8μs)

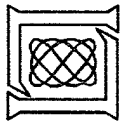


Topics

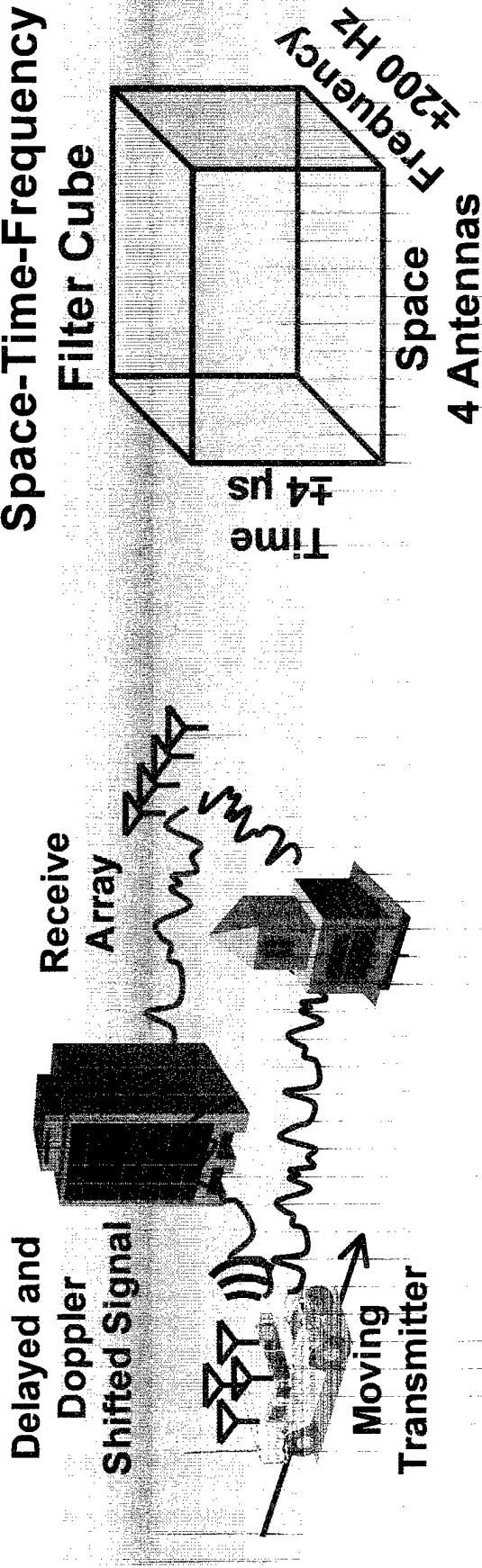
MIMO Communication

- Introduction
- MIMO Theory
- Phenomenology
- Receiver
 - Space-time-frequency adaptive processing
 - Multiuser detection
 - MCMUD
 - Experimental performance

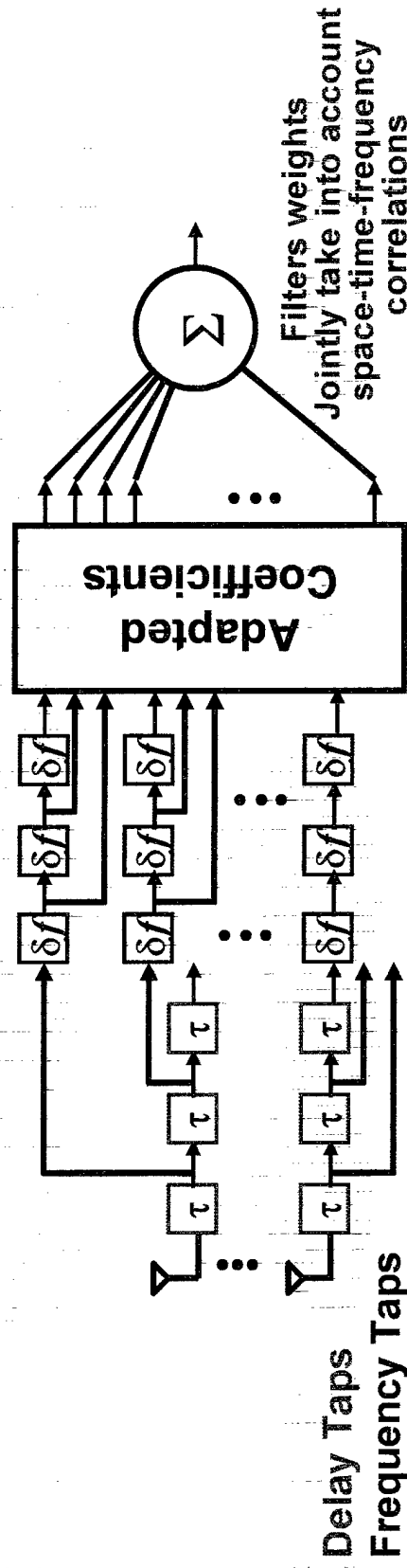


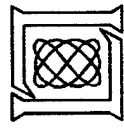


Adaptive Beamforming in Multipath

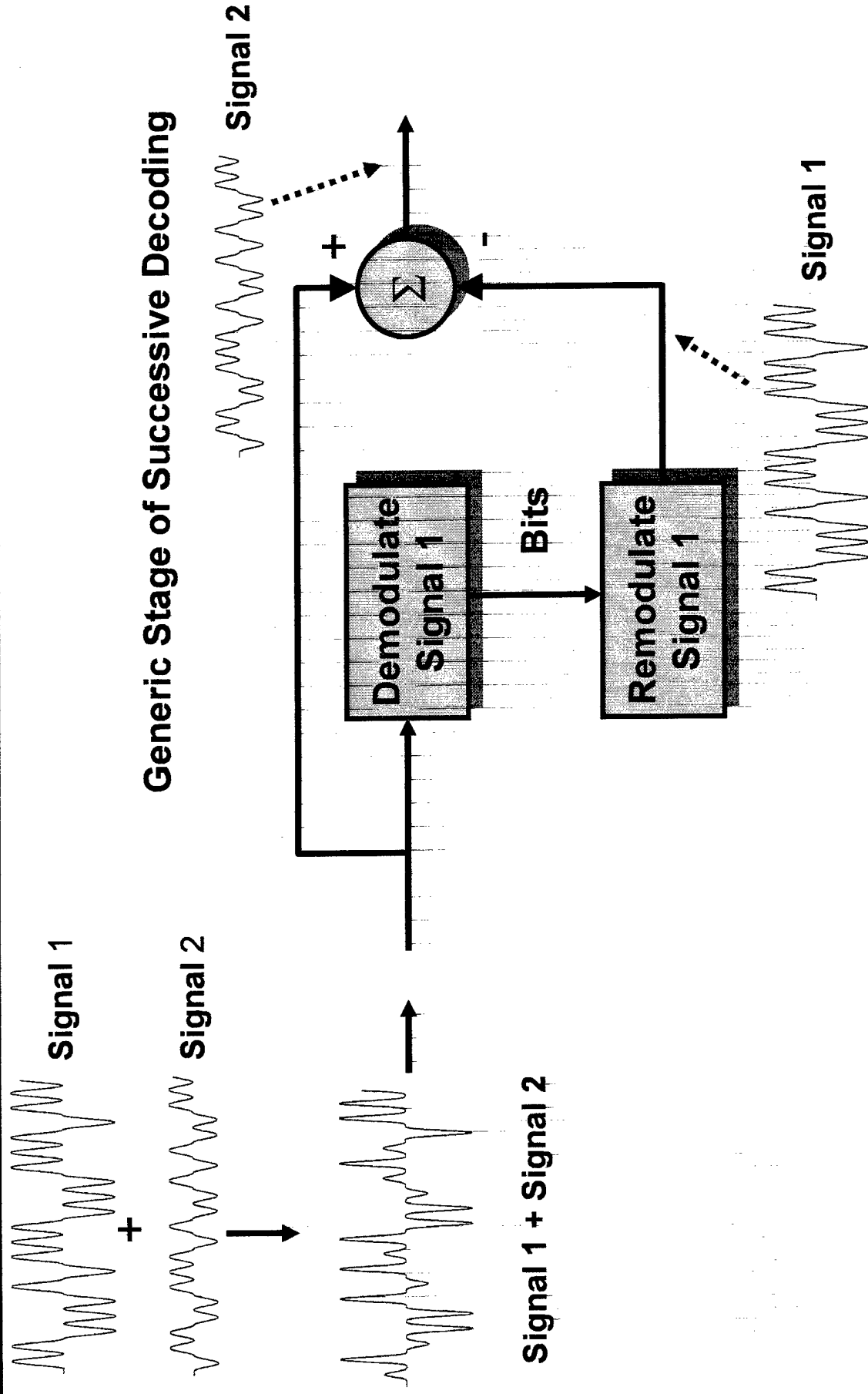


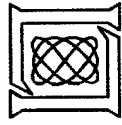
Space-Time-Frequency Adaptive Processing





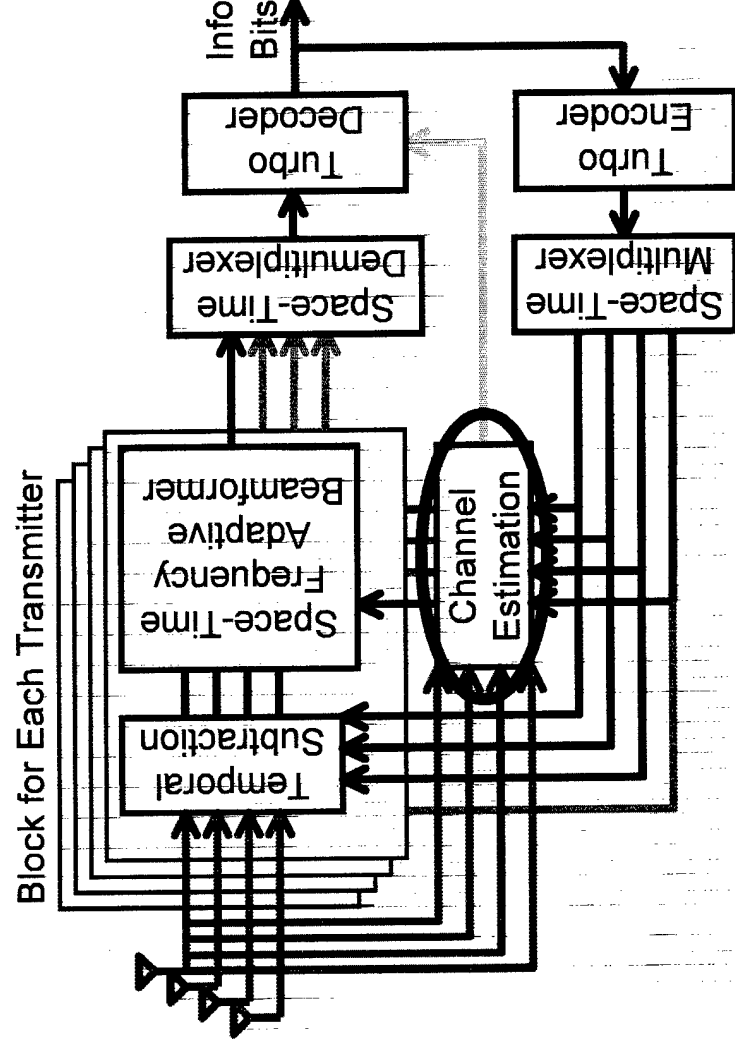
Notional Multiuser Detection

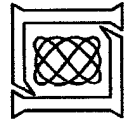




MCMUD for Space-Time Turbo Code

- Multichannel Multiuser Detector
(MCMUD, *pat. pending*)
- Iterative decoder
- Channel estimate
 - Training-based
 - Data-directed
- Estimation subtraction
(multiuser detection)
- Space-time-frequency
adaptive beamformers





MCMUD for Space-Time Turbo Code

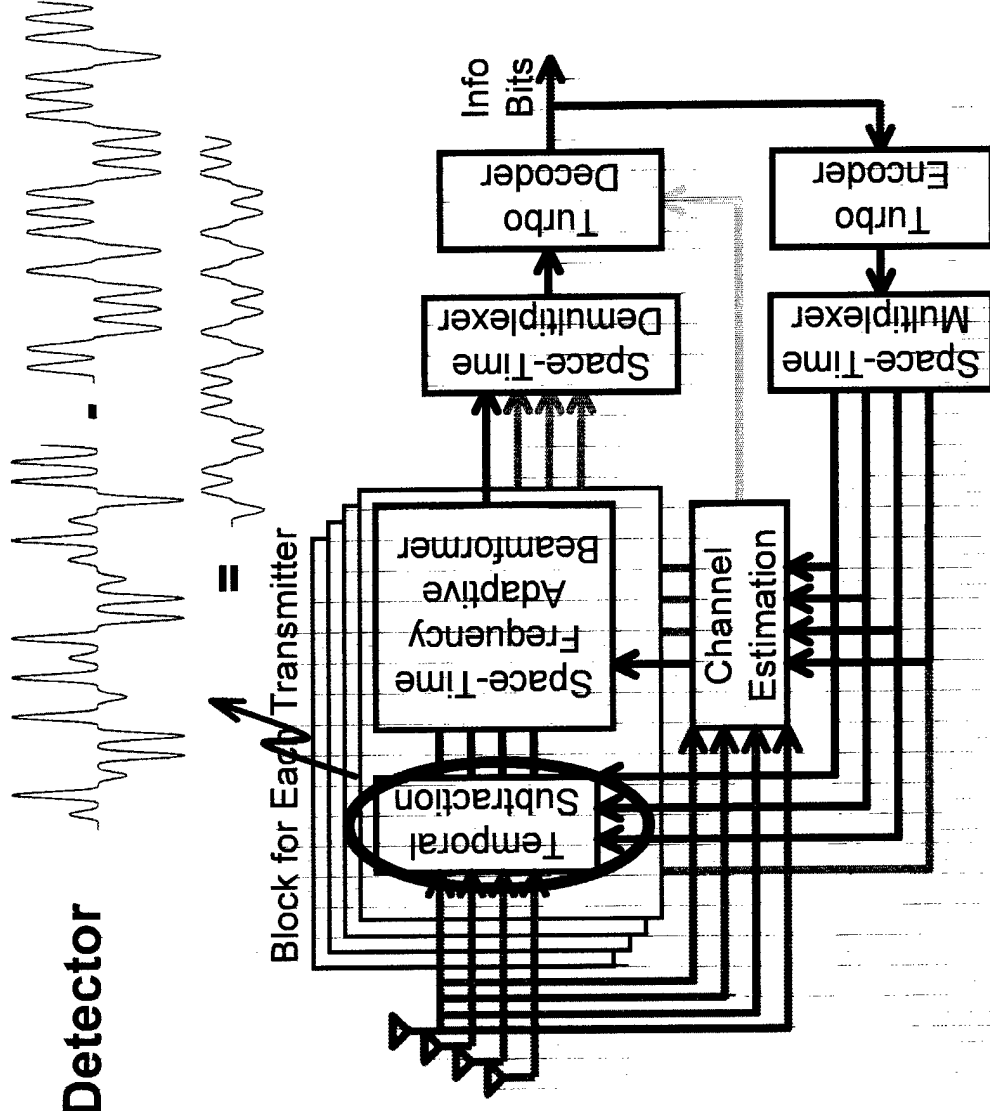
- Multichannel Multiuser Detector (MCMUD, *pat. pending*)

- Iterative decoder

- Channel estimate
 - Training-based
 - Data-directed

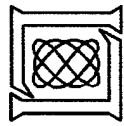
- Estimation subtraction (multiuser detection)

- Space-time-frequency adaptive beamformers



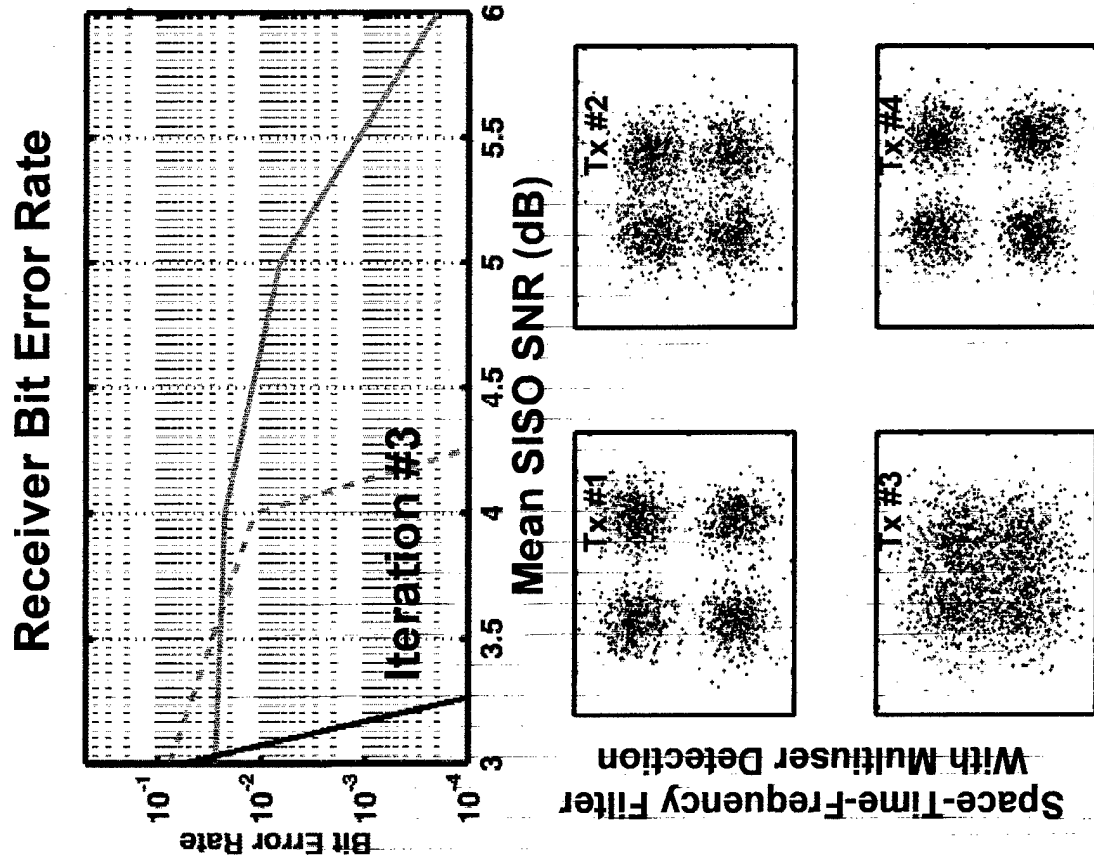
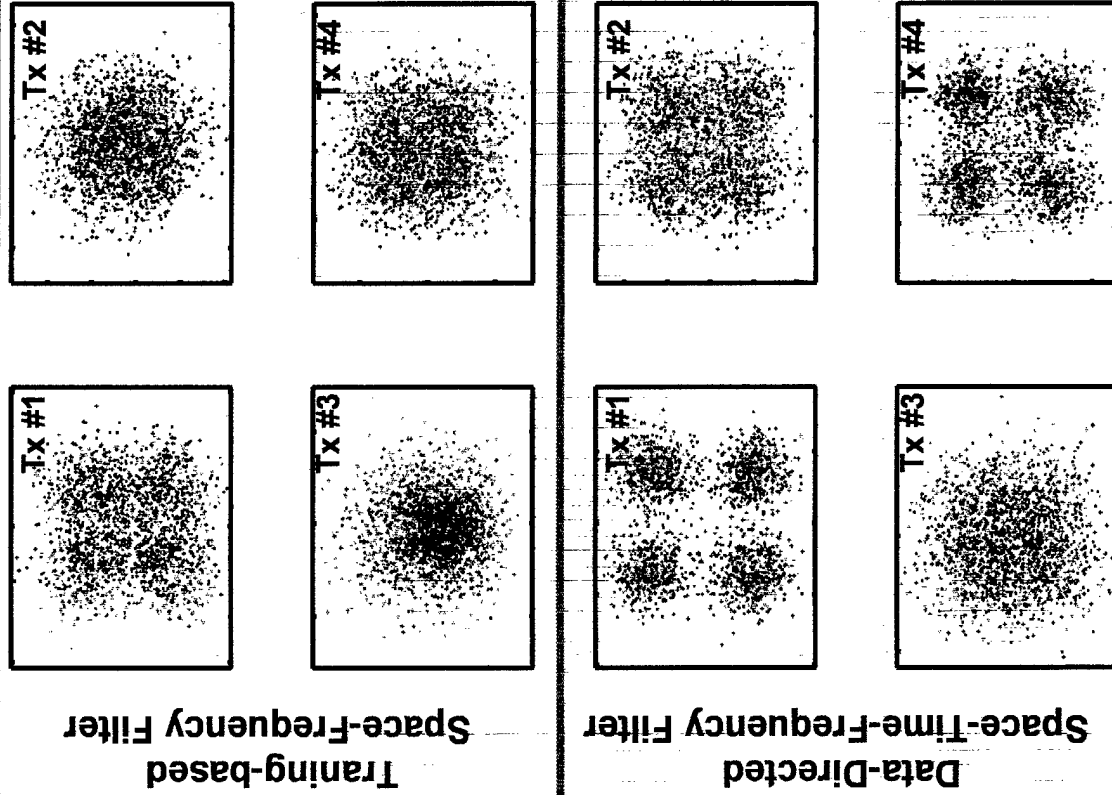


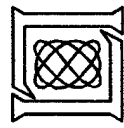
-
- The diagram illustrates a multi-user MIMO system. On the left, a 'Transmitter' section shows multiple antennas sending signals to a 'Block for Each Transmitter'. This block contains a 'Temporal Subtraction' module, a 'Space-Time Adaptive Beamformer' (circled in red), and a 'Channel Estimation' module. The 'Channel Estimation' module receives signals from all transmitters and provides feedback to the 'Space-Time Adaptive Beamformer' and the 'Space-Time Multiplexer' in the receiver. The receiver, on the right, consists of a 'Space-Time Multiplexer' that combines signals from all transmitters. This is followed by a 'Turbo Encoder' and a 'Space-Time Demultiplexer'. The 'Space-Time Demultiplexer' outputs signals to a 'Turbo Decoder', which produces the final 'Info Bits'. A feedback loop connects the 'Turbo Decoder' back to the 'Turbo Encoder'.



Experimental Results

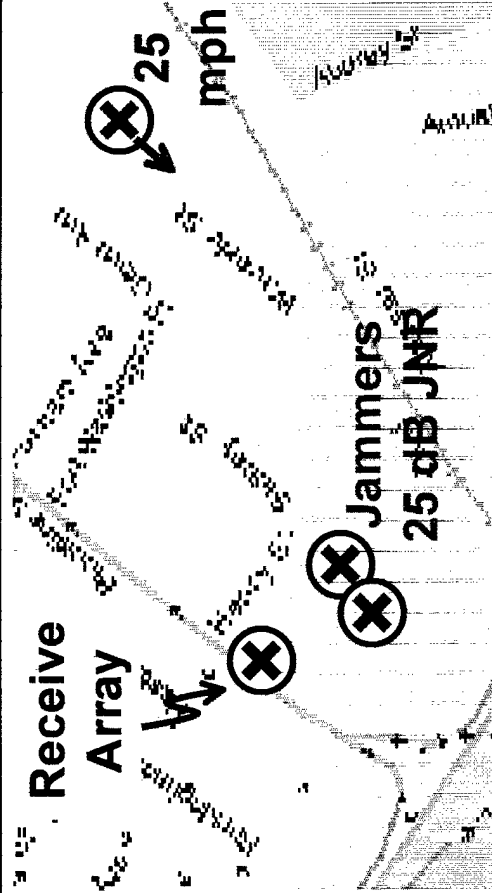
Successive MCMUD Iterations





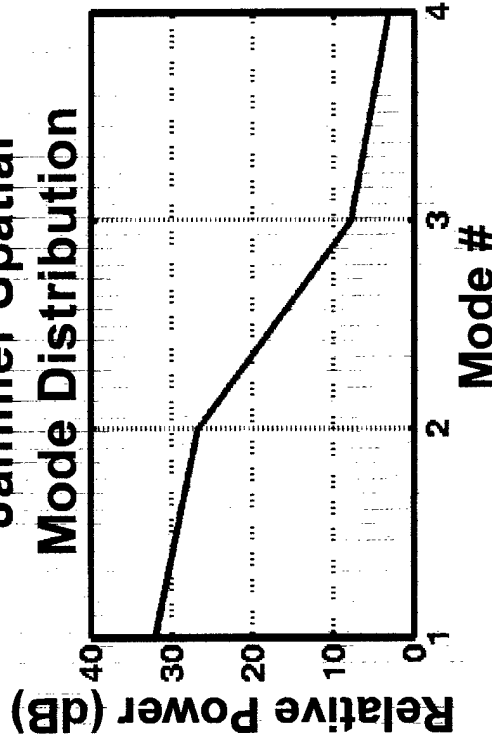
4x4 MIMO Performance

Motion, Jammers, and LO Errors

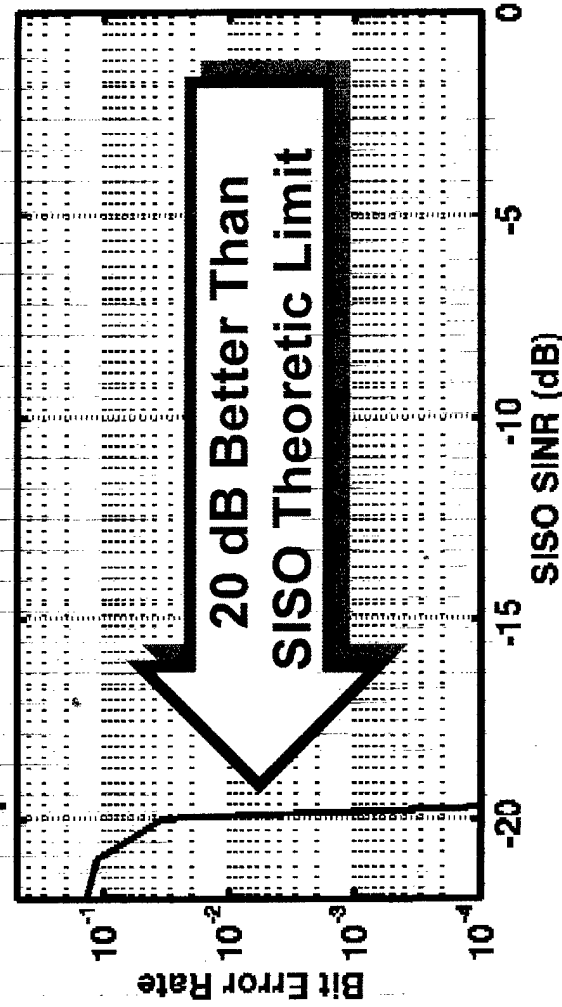


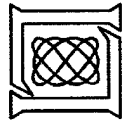
- 2 Noise Jammers (25 dB JNR)
- Moving transmitter (25 mph)
- Artificial relative local oscillator error (± 80 Hz)
- Error-free 2b/s/Hz data-link
- Near performance of jammer-free environment!

Jammer Spatial Mode Distribution



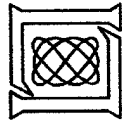
Experimental MIMO Performance





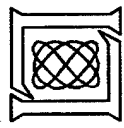
Summary

- **MIMO provides robust communication links**
- **New receiver design concepts (MCMUD) enable communication in complicated environments**
- **Demonstrated dramatic performance advantages using experimental data**
- **MCMUD enables coherent use of ad hoc distributed networks for MIMO communication**



Acknowledgements

- MIT Lincoln Laboratory
New Technology Initiative Board
- Experiment team
 - Sean Tobin, Jeff Nowak, Lee Duter, John Mann, Bob Downing, Peter Priestner, Bob Devine, Tony Tavilla, Andy McKellips, Gary Hatke
- Code, algorithm and experiment design
 - Keith Forsythe, Peter Wu, Ali Yegulalp
- Analysis support
 - Amanda Chan
- Students
 - Nick Chang (U. Mich),
Naveen Sunkavally (MIT)



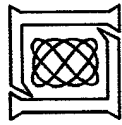
Backup Slides

Advanced Shoe-Phone Technology



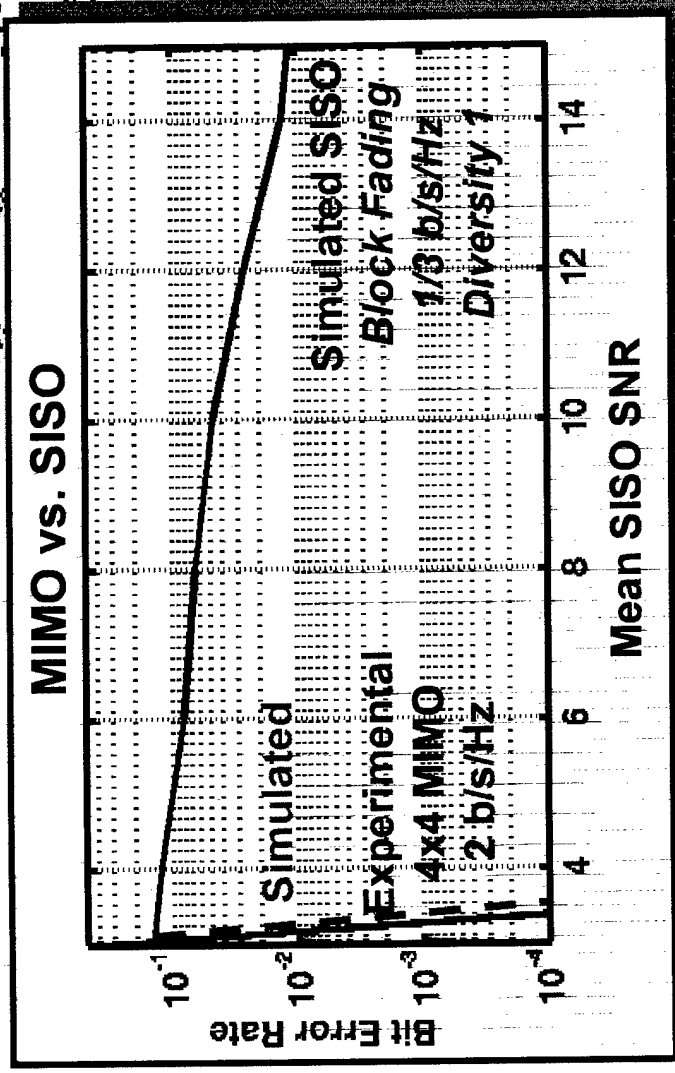
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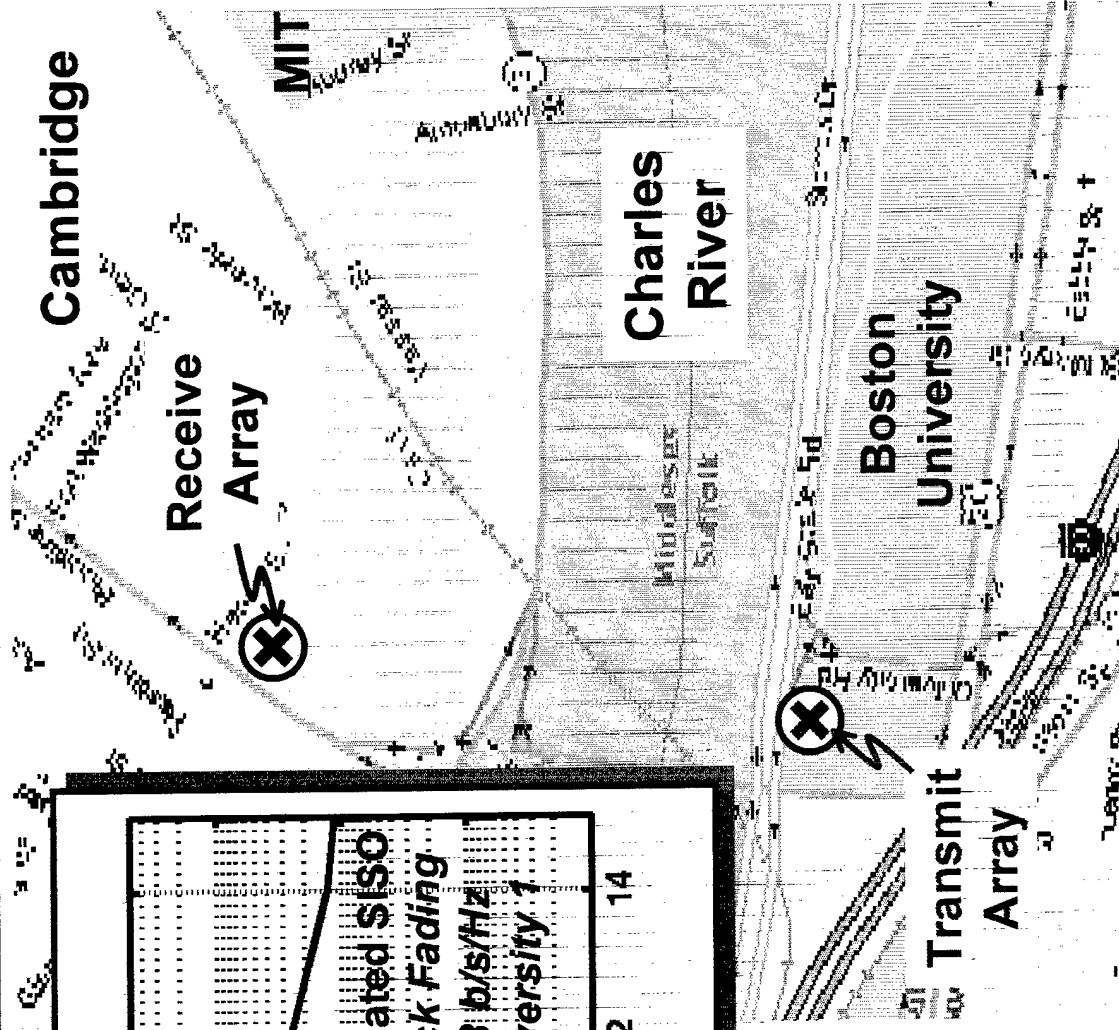


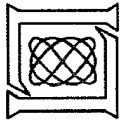
MIMO Ground-to-Ground Example

Non-Line-Of-Sight



- 4 x 4 MIMO performance dramatically better than SISO
 - 6 times bit rate
 - Fading resistance
- Significant Doppler introduced by fast vehicles on Storrow Dr.





Space-Time Codes Used in Experiment

4 Transmitters

- Alamouti (2 Tx), $\eta = 2$
- Block, $\eta = 3$
- Turbo, $\eta = 2$
- Turbo, $\eta = 4$
- CDMA, $\eta = 12/256$
- LDPC, $\eta = 1$
- LDPC, $\eta = 2$
- Trellis (Chen), $\eta = 2$

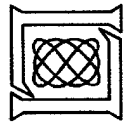
8 Transmitters

- Channel probe
- 2+2+2+2 Trellis, $\eta = 6$
- Block, $\eta = 3$
- Turbo, $\eta = 4$
- Turbo, $\eta = 8$
- CDMA, $\eta = 18/256$
- CDMA, $\eta = 20/256$
- LDPC, $\eta = 2$

Space-Time Code Source

- New Designs
- Provided by campus
- Literature

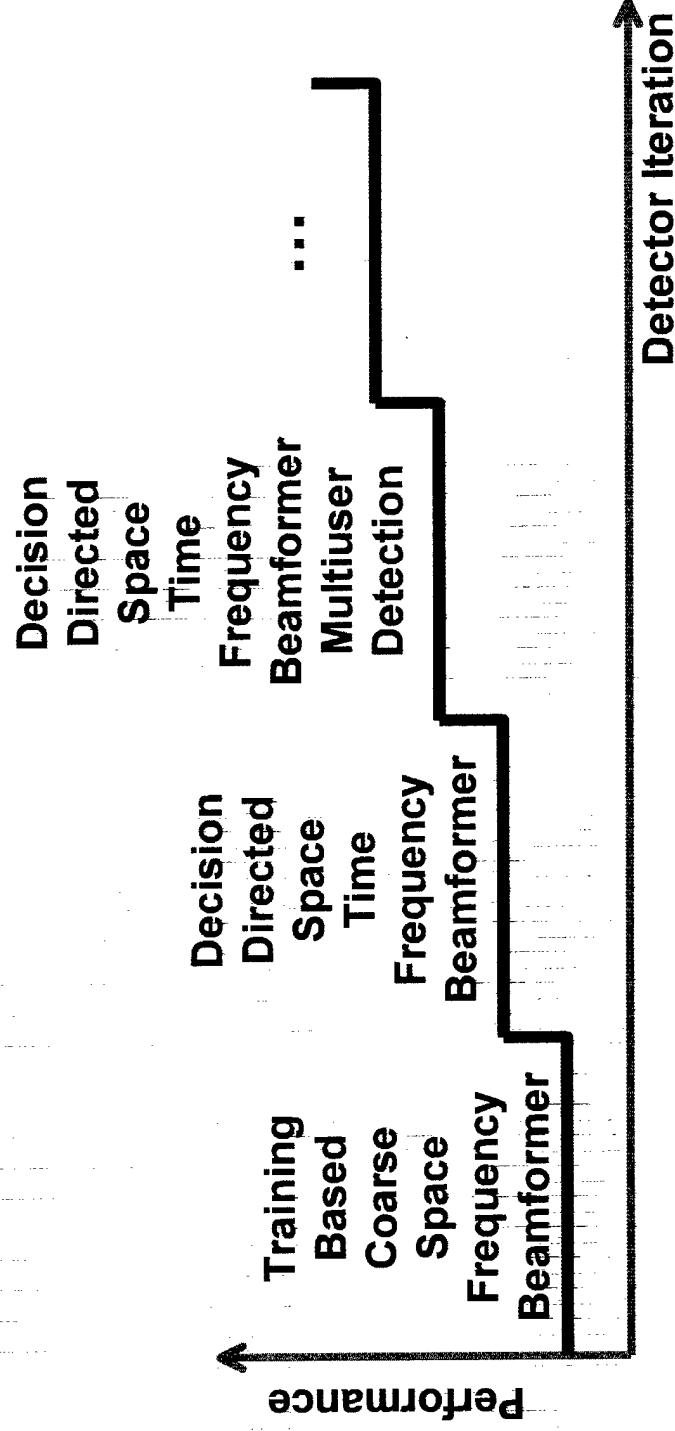
η – Spectral Efficiency (b/s/Hz)

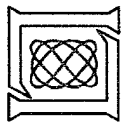


MCMUD Detector

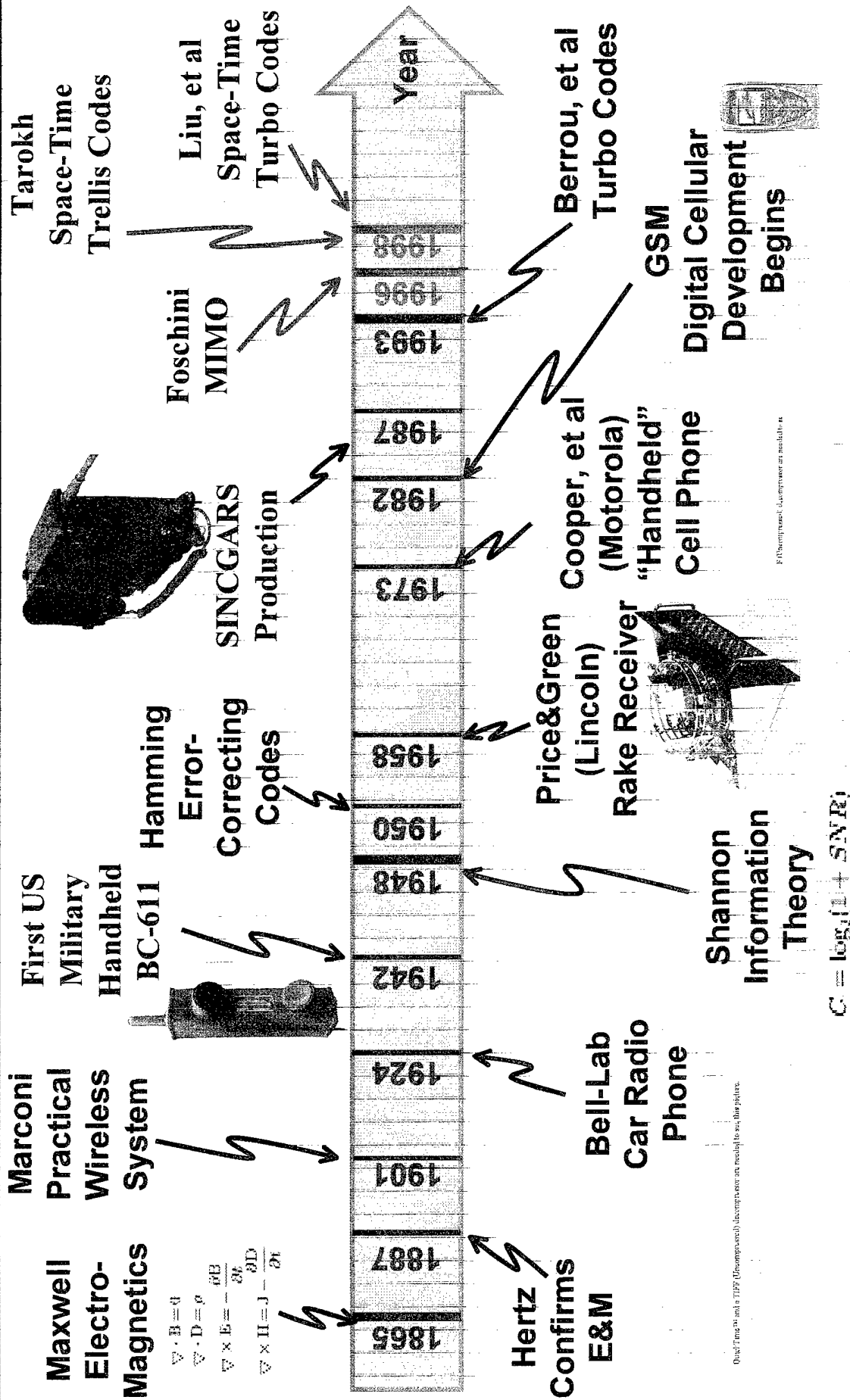
Progressive Complexity

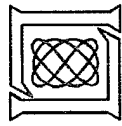
- Joint channel and data estimation
- First iteration access to limited training data or channel estimate from previous frame
- Increase detector complexity with iteration
- Increase number of turbo iterations with number of detector iterations





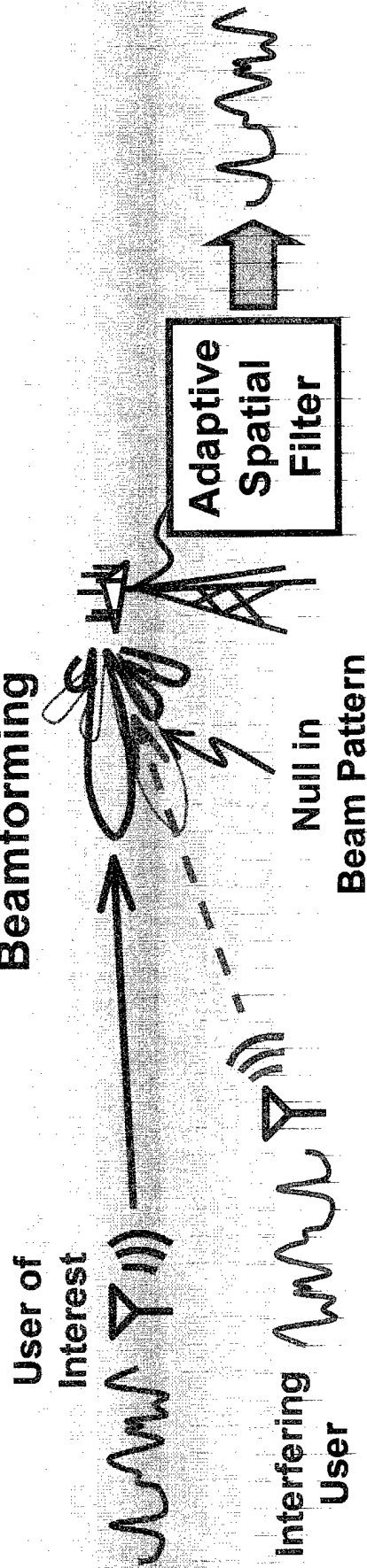
History of Wireless Communication



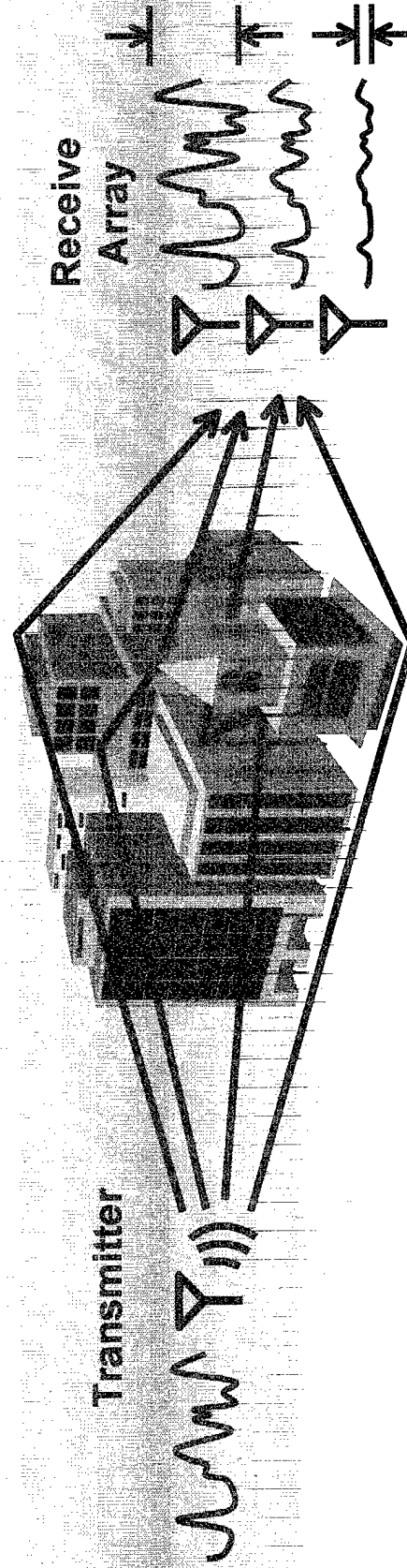


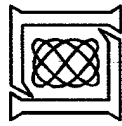
Important Antenna Array Concepts

Adaptive Spatial Beamforming



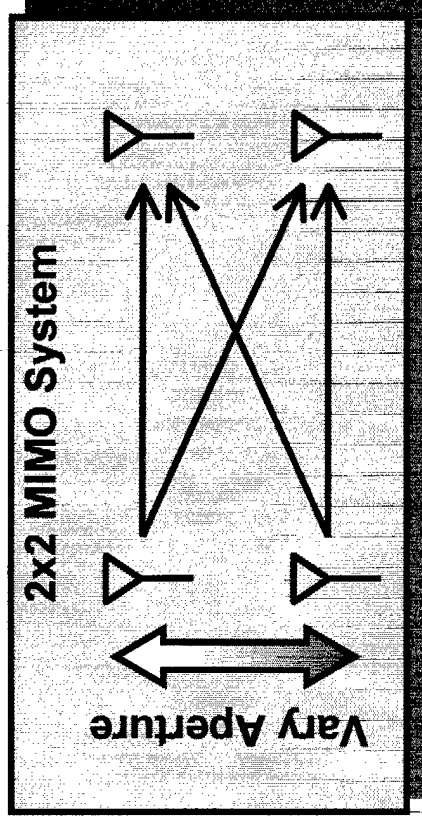
Diversity





The Channel Matrix

A Toy Model

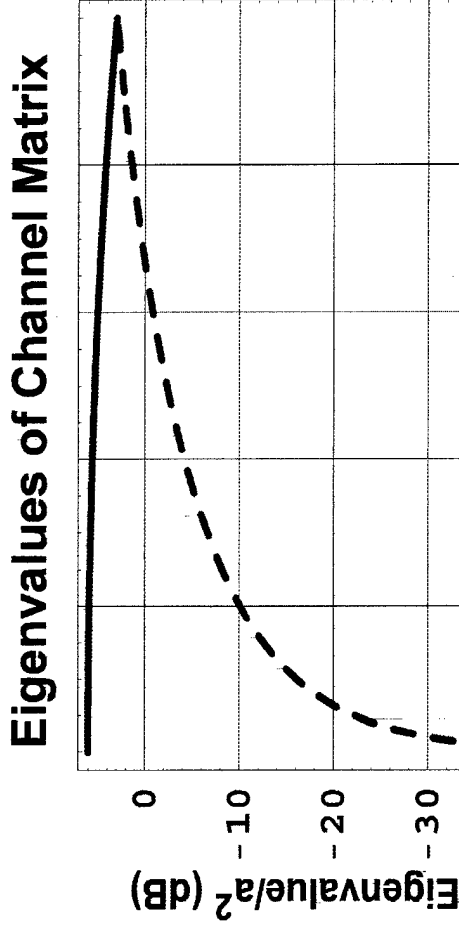


- Toy MIMO channel model

– 2x2

– line of sight

- Resolving individual antennas increases eigenvalue
- MIMO systems in real environments employ scatterers to increase effective aperture



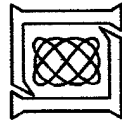
Generalized Beamwidth Separation

$$b = \frac{2}{\pi} \arccos \frac{\|h_1^+ h_2\|}{\|h_1\| \|h_2\|}$$

$$\text{Channel Matrix, } H = \begin{pmatrix} h_1 & h_2 \end{pmatrix} \\ = 2a \begin{pmatrix} \hat{v}_1 & \hat{v}_2 \end{pmatrix}$$

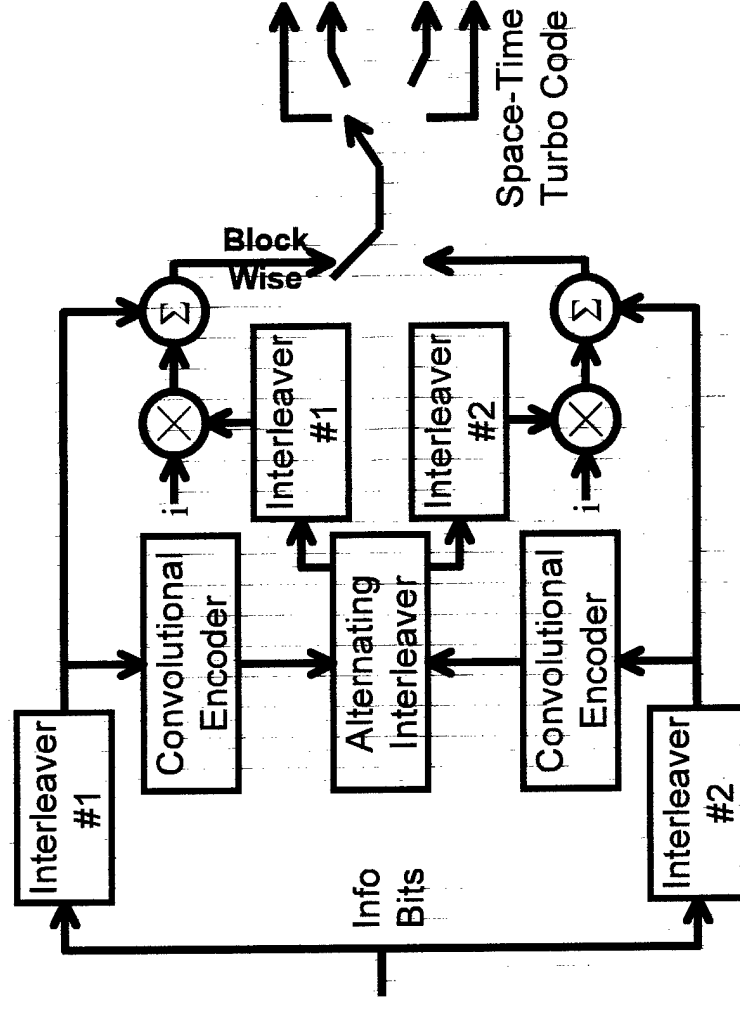
Unit norm
steering vector

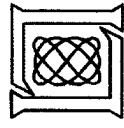
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Space-Time Turbo Code

- Block diagram for space-time turbo code
- Rate 2 b/s/Hz
- 123 kChip/s
- 4 Tx antennas
- 4096 bit interleavers
- QPSK constellation
- Optional training data





Uncooperative External Interference

Effective Loss of Complexity

- Uncooperative interference is equivalent to spatially correlated noise
- Covariance of interference plus noise

\mathbf{R}

- Maximize capacity by “decorrelating” channel matrix with respect to interference

$$\tilde{\mathbf{H}} = \mathbf{R}^{-1/2} \mathbf{H}$$

- Estimate $\tilde{\mathbf{P}}$ using new $\tilde{\mathbf{H}}$
- Modes near interference energy become less useful
- Effectively reduces the environmental complexity

Channel Capacity in Interference

Informed Transmitter (IT)

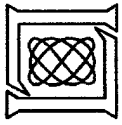
$$\tilde{C}_I = \max_{\text{tr}\{\tilde{\mathbf{P}}\}=P_0} \log_2 \left| \mathbf{I} + \tilde{\mathbf{H}} \tilde{\mathbf{P}} \tilde{\mathbf{H}}^+ \right|$$

Interference Whittened Channel Matrix

Noise-Normalized Transmittance Covariance Matrix

Uninformed Transmitter (UT)

$$\tilde{C}_{UT} = \log_2 \left| \mathbf{I} + \frac{P_e}{n_{Tx}} \tilde{\mathbf{H}} \tilde{\mathbf{H}}^+ \right|$$



The Channel Matrix

- Channel matrix, H , contains complex attenuation between each transmit and receive antenna
- Large channel eigenvalues of HH^H are useful

